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Device Application of Surface Modulation Technique Using CW Laser Beam

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Device applications of the surface relief grating (SRG) using surface modulation by a continuous laser beam are described. SRGs are directly fabricated in azo-polymer films by the surface modulation using interference fringes of circular polarized Ar-ion laser beams at the wavelength of 488 nm without etching processes. This surface modulation is fabricated by mass transport of the polymer chains and the surface relief depth is determined by the irradiation power and time. The maximum depth is related to the film thickness and it is about 300 nm when the film thickness is about 1μm. Surface relief electro-optic gratings (SREOGs) are fabricated by poling the SRG. We fabricated the transmission type and reflection type SREOG. The plane Indium Thin Oxide electrode and the sinusoidal type electrode evaporated by Aluminum is used to apply the voltage, respectively. In the transmission type, we observed the linear dependence of an applied voltage by EO effect in the modulation efficiency of the first-order diffraction beam. In the reflection type, we observed the strong polarization dependence in the modulation efficiency and diffraction efficiency.

Key words: azo-polymer film, surface relief grating, electro-optic effect, corona poling, polarization

1. INTRODUCTION

Direct fabrication of a surface relief grating (SRG) in azobenzene functionalized polymer films has been reported.[1-3] This SRG has been fabricated by the irradiation of two-beam interference fringes at an absorbing wavelength. The fabrication beam power is a few tens mW/cm^2 and the fabrication temperature is below the glass transition temperature (Tg). The surface modulation is also related to the polarization of the laser beam[4] and the large surface modulation (≈1 μm) has been reported in this method.[2] This grating is very stable at a temperature under Tg and can be erased by the irradiation of the laser beam under Tg[5] or by heating this SRG above Tg. The fabrication mechanism of this SRG is not well understood at present, but several models of this mechanism has been proposed by Tripathy and his colleagves.[6-8] We are very interested in fabrication of optical elements using this mechanism. The advantages of this method are open-air operation, a short fabrication time and a direct etching and this technique can simplify the device fabrication process. But at present, the interest of research is to make the fabrication mechanism clear. The application example to the device is a little, but a grating coupler[9] and a guided mode resonance filter[10] using this SRG were reported.

We have also reported about the SRG fabrication which used polyurethanes with orange Tom-1 side groups[11] and the modulation result in surface relief electro-optic grating (SREOG) using this SRG.[12] This fabrication method is very easy and the SREOG is fabricated by poling the SRG at a temperature under Tg without erasing the surface relief. This method can simplify the device fabrication process and be used the fabrication of diffraction optical elements having EO effect.

In this paper, we describe the device application of the SRG using surface modulation by CW laser beam. SRGs are directly fabricated in azo-polymer films using interference fringes of circular polarized Ar-ion laser beams at the wavelength of 488 nm without etching processes. SREOG is fabricated by poling the SRG after the SRG fabrication process. We fabricated the transmission type and reflection type SREOG (TSREOG and RSREOG). The plane Indium Thin Oxide electrode and the sinusoidal type electrode evaporated by Aluminum (Al) is used to apply the voltage, respectively. Modulation of the EO effect and polarization dependence in the first-order diffraction beam power is observed.

2. FABRICATION OF SREOG

The side-chain type azo-polymer, poly-orange Tom-1 Isophoronediisocyante is used in this study. The molecular structure and the optical characterization of this polymer have been described elsewhere.[11] The concentration of dye is 18 wt% and Tg is 136 ℃. This polymer is dissolved in cyclohexanone. Samples are prepared by spin-coating on a pyrex glass plate with ITO electrodes and baked at 90 ℃ over night to remove the solvent. The thickness of the polymer film is about 1 μm.

SRGs are fabricated by the irradiation of two-beam interference fringes. The experimental setup and the relation between the relief depth and the irradiation time, the irradiation power has been described elsewhere.[12] Circular polarized Ar-ion laser beam at the wavelength of 488 nm is used as the light source, because the relief depth fabricated by circular polarization is higher than that fabricated by linear polarization.[4] The relief depth of the SRG is also related to the polymer thickness, irradiation power and irradiation time. The SRG with optional depth can be fabricated by controlling these conditions. When the film thickness is about 1 μm, the maximum depth is about 300 nm. In this experiment, SRGs are fabricated by next condition: the irradiation power is 50 mW/cm^2, the irradiation time is 30 min, the period of interference fringe is about 1μm.

SREOGs are fabricated by the corona poling. SRGs are poled at a temperature under Tg by applying a 7 kV dc voltage in the oven, because the grating by the surface deformation method is erased thermally by heating the polymer film to above Tg.

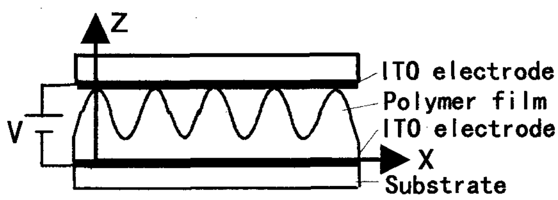

Fig.1. Electrode structure of TSREOG.

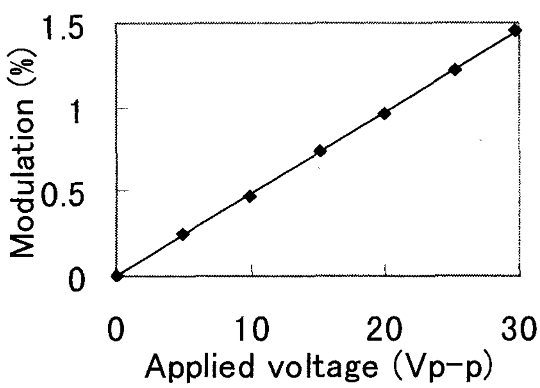

Fig. 2. Modulation efficiency of the first-order diffraction beam power. The modulation frequency is 1 kHz.

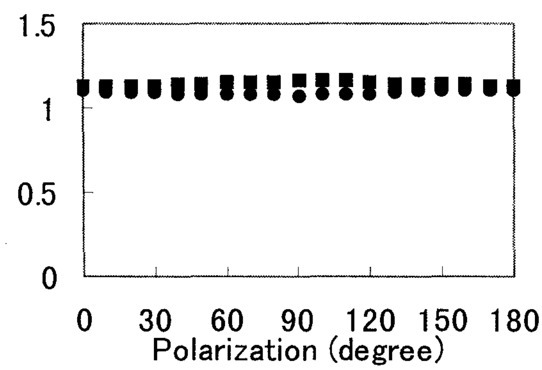

Fig. 3. Polarization dependence of the diffraction efficiency (filled squares) and the modulation efficiency (filled circles). Alternating current voltage of 1 kHz with 30 Vp-p is applied.

3. MODULATION OF TSREOG

Modulation of the EO effect at the wavelength of 633 nm is observed by modulating the first-order diffraction beam power. The electrode structure of TSREOG is shown in Fig. 1. The voltage to the sample is applied between the top and bottom of the SREOG by inserting a glass substrate with ITO electrodes. This electrode structure is special as the appling voltage method. But we use this structure to observe the modulation by EO effect, because the fabrication is very easy. Modulation of the first-order diffraction beam power is measured by a lock-in amplifier. The modulation efficiency ($\Delta\eta_1/\eta_1$) of the first-order diffraction beam power vs. applied voltage is shown in Fig. 2; this is the result of modulation of the SRG (η_1=12.1) by the surface deformation method. The modulation efficiency is proportional to an applied voltage and that value at 1 kHz with 30 Vp-p is 1.45 %. In the same examination using an unpoled sample, modulation is not observed.

The SRG using the surface deformation generally shows the polarization dependence by the effect of light orientation.[13] Therefore, we measured the polarization dependence of the diffraction efficiency and the modulation efficiency in the first-order diffraction beam power, when the alternating current voltage of 1 kHz with 30 Vp-p is applied. The modulation result is shown in Fig. 3. The laser beam is perpendicularly inputted in the TSREOG (direction of the z axis) and passes in order of polymer film, SRG. In the polarization, 0° (perpendicular to the grating vector) and 90° (parallel to the grating vector) are equivalent to s and p polarization, respectively. We confirmed that the polarization dependence occurred hardly in the diffraction efficiency and the modulation efficiency. From this result, the film is isotropic against the perpendicular input beam.

4. MODULATION OF RSREOG

The RSREOG is fabricated by evaporating an Al on the SREOG. This evaporated Al is used as the mirror and the electrode. Modulation of the EO effect is observed by modulating the first-order diffraction beam power. The electrode structure is shown in Fig.4. The voltage to the sample is applied between the sinusoidal type Al electrode and the plane ITO electrode. The laser beam is perpendicularly inputted from the side of glass substrate. The diffraction efficiency (η_1) and the modulation efficiency ($m=\Delta\eta_1/\eta_1$) of the first-order diffraction beam vs. the polarization are shown in Fig. 5. In the polarization, 0° (perpendicular to the grating vector) and 90° (parallel to the grating vector) are equivalent to s and p polarization, respectively. The alternating current voltage of 1 kHz with 30 Vp-p is applied. The strong polarization dependence is observed. High diffraction efficiency is obtained for s polarization and the ratio of s polarization and p polarization (η_{1s}/η_{1p}) is 16. The diffraction efficiency when perpendicularly inputted from the side of Al electrode is shown in Fig. 6. The polarization dependence of the first-order diffraction efficiency is stronger than that when perpendicularly inputted from the side of the substrate. The ratio of s polarization and p polarization (η_{1s}/η_{1p}) is 20. Therefore, the polarization character of the RSREOG depends on the character of SRG evaporated Al strongly. On the other hand, high modulation efficiency is obtained for p polarization and the ratio of p polarization and s polarization (m_p/m_s) is 126. When the modulation is showed by using the modulation efficiency, there is time when the modulation becomes big outwardly; this means that the modulation with the smaller diffraction efficiency becomes bigger as the modulation efficiency, when the modulation size is the same approximately. Therefore, the measured data are shown in Fig.5. We find that the modulation size becomes big though the diffraction beam power decreases, when the polarization is changed from 0° to 90°. The ratio of the modulation size is 8 and this ratio is bigger than the ratio with r coefficient ($r_{33}/r_{13}\approx3$).

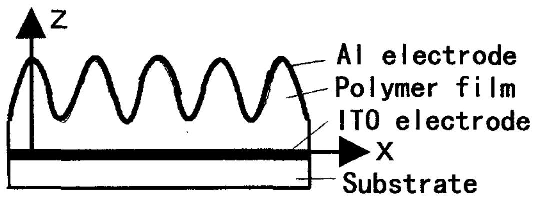

Fig. 4. Electrode structure of RSREOG.

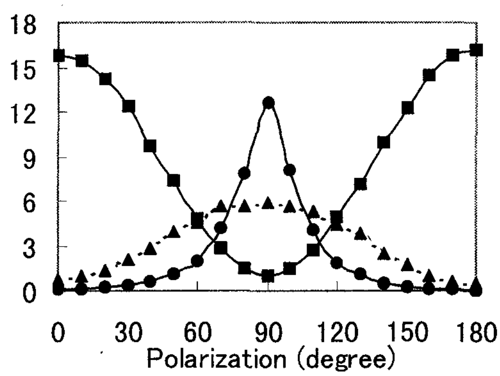

Fig. 5. Polarization dependence of the modulation efficiency (filled circles), the diffraction efficiency (filled squares) and measured value (filled triangles). Alternating current voltage of 1 kHz with 30 Vp-p is applied.

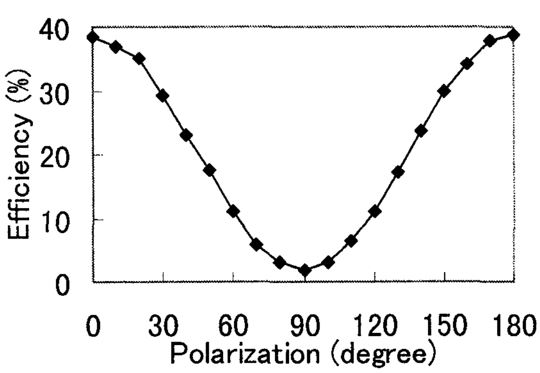

Fig. 6. Diffraction efficiency when perpendicularly inputted from the side of Al electrode.

5. Origin of modulation and polarization character

Modulation and polarization character of each type SREOG can be analyzed by considering the change of the refractive ellipsoid occurred by EO effect and the refractive ellipsoid, respectively. Still more, the modulation is achieved by producing the phase difference in the path of the beam. In the SREOG, this phase difference is produced by the refractive index difference between the polymer layer that is changed by electric field and the air layer that doesn't change. We define the coordinate system shown in Fig. 1, Fig. 4. x is the same direction as grating vector and y is the perpendicular direction against grating vector. z is the propagation direction of the laser beam.

In the TSREOG, an appling electric field to the polymer film is different partially and has a component to the x direction in addition to the z direction, because the air layer exist between the electrodes. When the polarization is aligned to the z direction by the corona poling, the refractive ellipsoid by the electric field to the z direction is given by

$$\frac{x^2}{n_x^2}+\frac{y^2}{n_y^2}=1 \qquad (1)$$

with

$$n_x = n_y = n_o + \frac{r_{13}n_o^3E_z}{2} \qquad (2)$$

where n_x, n_y is the refractive index in the x direction and y direction, respectively. r_{13} is the EO coefficient in the x direction. E_z is the applied electric field to the z direction. The refractive ellipsoid by the electric field to the x direction is given by

$$\frac{x^2}{n_0^2}+\frac{y^2}{n_0^2}=1 \qquad (3)$$

Equation (3) shows that even if the electric field component to the x direction exists, the refractive index change doesn't occur. Therefore, we should consider only an electric field component to the z direction. Therefore, the modulation occurs by the difference of the applied voltage to the z direction. From equation (2), TSREOG is isotropic against all polarization. This result agrees with the experimental result shown in Fig. 3.

In the RSREOG, the modulation and the polarization character is quite complicated from the experimental result. An appling electric field to the polymer film is different partially and has a component to the x direction in addition to the z direction, because of the sinusoidal electrodes. Generally, the phase difference depends only on the applied voltage in this electrode structure. When we think that the distribution of EO coefficient is constant in the polymer film, the phase difference does not occur and the modulation does not observed. Therefore, it is necessary to think that the distribution of EO coefficient is different in the polymer film. In this experiment, the SREOG is fabricated by corona poling. It is sufficiently estimated that the poling distribution of the thick part and the thin part are different, when we thinks about the characteristic of the corona discharge. We think that the phase difference occurs with the refractive index difference between the thick part and the thin part by the EO effect. In the modulation of RSREOG, it is necessary to think about the following two parts: the modulation before the Al mirror reflection and the modulation after the Al mirror reflection.

When the modulation before the Al mirror reflection is thought, the laser beam moves ahead perpendicularly to the polymer surface. This condition is same as the TSREOG and the polarization dependence does not occur. Therefore we think that the polarization dependence occurs by the modulation after the Al mirror reflection.

When the modulation after the Al mirror reflection is thought, the laser beam moves ahead diagonally to the polymer surface. The index ellipsoid by the electric field to the z direction is given by

$$\frac{x^2}{n_x^2}+\frac{y^2}{n_y^2}+\frac{z^2}{n_z^2}=1 \qquad (4)$$

with

$$n_z = n_o + \frac{r_{33} n_e^3 E_z}{2} \qquad (5)$$

where n_z is the refractive index in the z direction. r_{33} is the EO coefficient in the y direction. E_z is the applied electric field to the z direction. n_x, n_y is given by equation (2). The index ellipsoid is anisotropic against the polarization and it is possible that the polarization dependence occurs. But the ratio of the modulation in this case is 3 times in the maximum and this ratio is smaller than the experimental value. The index ellipsoid by the electric field to the x direction is given by

$$\frac{x^2}{n_0^2}+\frac{y^2}{n_0^2}+\frac{z^2}{n_e^2}+2r_{13}E_x zx=1 \qquad (6)$$

In this case, the axis turn of the index ellipsoid happens by the electric field to the x direction. From above thing, we think that the polarization dependence occur by both the electric field to the x direction and z direction. However, there are actually many uncertain parts such as the distribution of the poling in the polymer film and it is difficult for them to specify cause. A few experiments and the modeling of structure are necessary.

6. CONCLUSION

We have described the device application of the SRG using surface modulation by CW laser beam. SRGs are directly fabricated in azo-polymer films by the surface modulation using interference fringes of circular polarized Ar-ion laser beams at the wavelength of 488 nm. SREOGs are fabricated by poling the SRG at a temperature under Tg after the SRG fabrication process. We fabricated the transmission type and reflection type SREOG. The plane Indium Thin Oxide electrode and the sinusoidal type electrode evaporated by Al is used to apply the voltage, respectively. In the transmission type, we observed the linear dependence of an applied voltage by EO effect in the modulation efficiency of the first-order diffraction beam. In the reflection type, we observed strong polarization dependence in the modulation efficiency and the diffraction efficiency.

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REFERENCES

1. D.Y. Kim, Lian Li, X.L.Jiang, V. Shivshankar, J. Kumar and S. K. Tripathy, *Macromolecules.*, **28**, 8835-839 (1995).
2. C. J. Barrett, A. L. Natansohn and P. L. Rochon, *J. Phys. Chem.*, **100**, 8836-842 (1996).
3. N. C. R. Holme, L. Nikolva, P. S. Ramanujam, and S. Hvilsted, *Appl. Phys. Lett.*, **70**, 1518-520 (1997).
4. X. L. Jiang, L. Li, J. Kumar, D. Y. Kim, V. Shivshankar and S. K. Tripathy, *Appl. Phys. Lett.*, **68** 2618-620 (1996).
5. X. L. Jiang, L. Li, J. Kumar, D. Y. Kim and S. K. Tripathy, *Appl. Phys. Lett.*, **72**, 2502-504 (1998).
6. J. Kumar, L. Li, X. L. Jiang, D. Y. Kim, T. S. Lee and S. Tripathy, *Appl. Phys. Lett.*, **72**, 2096-98 (1998).
7. S. Bian, L. Li, J. Kumar, D. Y. Kim, J. Williams and S. K. Tripathy, *Appl. Phys. Lett.*, **73**, 1817-819 (1998).
8. K. Sumaru, T. Yamanaka, T. Fukuda, H, Matsuda, *Appl. Phys. Lett.*, **75**, 1878-880 (1999).
9. J. Paterson, A. Natansohn, P. Rochon, C. L. Callender and L. Robitaille, *Appl. Phys. Lett.*, **69**, 3318-320 (1996).
10. P. Rochon, A. Natansohn, C. L. Callender and L. Robitaille, *Appl. Phys. Lett.*, **71**, 1008-1010 (1997).
11. M. Itoh, K. Harada, H. Matsuda, S. Ohnishi, A. Parfenov, N. Tamaoki and T. Yatagai, *J. Phys. D: Appl. Phys.*, **31**, 463-471 (1998).
12. K. Munakata, K. Harada, N. Yosikawa, M. Itoh, S. Umegaki and T. Yatagai, *Opt. Rev.*, impress.
13. I. Naydenova, L. Nikolova, T. Todorov, N. C. R. Holm, P. S. Ramanujam and S. Hvilsted, *J. Opt. Soc. Am.*, **B15**, 1257-265 (1998).

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